

OPTICAL SOLITON & APPLICATIONS THEREOF

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ABSTRACT

The combined effects of dispersion and nonlinearity of the pulse propagation can generate stable and undistorted pulses which is called soliton. Optical soliton pulses running over long distances is very useful for transmitting high data rate information in optical fiber. The versatile applications of the optical soliton have attracted the attention of the experimental as well as theoretical physicists. Hence, the main objective of this study is the introduction to optical soliton and its applications.

KEYWORDS: Soliton, SPM, GVD

INTRODUCTION

It is widely acclaimed that the phenomenon *soliton* was first recorded by John Scott Russell in 1834. He observed during a horse-back ride along the Union Canal near Edinburgh that a single pulse of fluid detached from the main stream running unchanged along the canal for several miles. Russell named this wave as 'great solitary wave'. Similar phenomenon was also observed later on through various analysis and experiments. Optical Soliton means a light beam or pulse propagating through a non-linear optical medium without any change in its shape and velocity. Solitons in non-linear optical fibers is widely used in communication, optical computing, optical switching, etc. [10]

SOLITON PHYSICS

The soliton compensates linear pulse dispersion by nonlinear pulse compression. However, it is imperative to understand the cooperating phenomena of *dispersion* and *self phase modulation*. [1-2]

Dispersion

Pulse Dispersion means the spreading out of the pulses while travelling down the fiber as shown in the following figure:

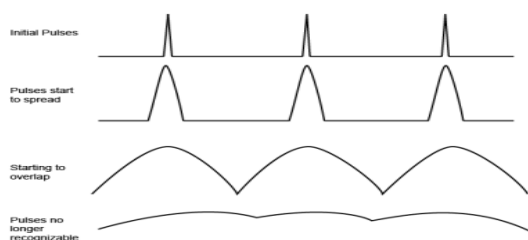


Figure 1: Pulse Dispersion

The dispersions are either due to intra-modal or inter-modal delay effects which cause the spreading of the pulses passing through a fiber and its effects are based on group velocities of the guided modes. Group velocity means the speed

at which energy travels along the fiber in a particular mode. The intra-modal dispersions occur due to material and wave guide dispersions. Material dispersion arises due to the variation in refractive index of the core of the fiber as a function of wavelength. On the other hand waveguide dispersion occurs in single mode fibers because only 80% of the optical power is concentrated to the core while 20% of the optical power is concentrated to the cladding which causes distortion because velocities of the pulse in the cladding and that in the core have different values. Each mode has different values for the group velocities causing distortion due to intramodal delay in multi-mode fibers. The full effects of these distortions are rarely observed in practice because various other factors are working simultaneously, e.g., non ideal index profiles, optical power-launching conditions, non uniform mode attenuation, etc. An instant effect of dispersion is that the light pulse travels through the fiber and its shape gets broadened. The group velocity i.e., the velocity at which the energy in a pulse travels in a fiber, is given by:

$$V_g = d\omega/dk \quad (1)$$

This is also called as the velocity of the envelope wave. The component waves and their superposition (the envelope) will travel with the same velocity in a non dispersive medium. Accordingly, the shape of the pulse (envelope) remains unchanged as the pulse propagates through the medium. However, this is not a common situation because the velocity in an optical medium depends on the refractive index which ultimately depends on the frequency of the wave, i.e, wavelength. The phase velocity of a wave is $\omega/k = v = c/n$; where c is the velocity of the wave in vacuum and n is the refractive index of the medium. Each spectral component travels independently with a time delay per unit wavelength. The propagation time over a distance can be defined as L for a given group velocity V_g as $\tau = L/V_g$. The delay difference per unit wavelength along the propagation path is given by $d\tau/d\lambda$ if the spectral width of the pulse is not wide. If the wave-lengths of spectral components are spread over a wavelength range $\delta\lambda$, the total delay difference $\delta\tau$ over a distance L is given by:

$$\delta\tau = \frac{d\tau}{d\lambda} \delta\lambda = -\frac{L}{c} \lambda \frac{d^2n}{d\lambda^2} \delta\lambda \quad (2)$$

The spread in arrival times depends on $(d^2n/d\lambda^2)$. The different component waves constituting the pulse have different phase velocities. The pulse is, therefore, spread out as it moves along the fiber. This phenomenon is called Group Velocity Dispersion (GVD). Here under is a quantity called mode propagation constant $\beta = n(\omega)\omega/c$ with a Taylor series expansion :

$$\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + \dots \quad (3)$$

Where of $\beta_m = (d^m\beta/d\omega^m)$, $m=1, 2, 3...$ A little bit of algebra will show that:

$$\beta_2 = \frac{d\beta_1}{d\omega} = \frac{\lambda^3}{2\pi c_0^2} \frac{d^2n}{d\lambda^2} \quad (4)$$

Here β_2 is known as GVD parameter. Another quantity known as total dispersion parameter widely used in the literature is defined as:

$$D_\lambda = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta_2 \quad (5)$$

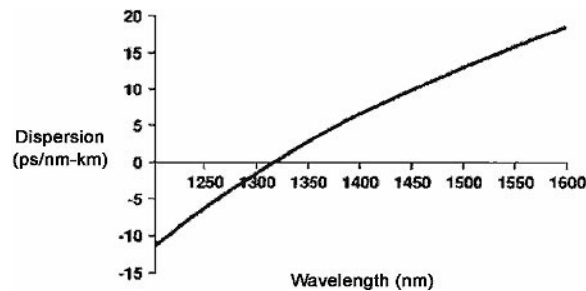


Figure 2: Wave-Length Dependence of the Dispersion Parameter D for Standard Fiber

Figure 2 reveals that D_λ increases and vanishes at a wave-length around 1310 nm which is called zero dispersion wave-length λ_D . For $\lambda < \lambda_D$, $\beta_2 > 0$ and the fiber shows normal dispersion, while for $\lambda > \lambda_D$, $\beta_2 < 0$ and the fiber shows anomalous dispersion. The high frequency components of an optical pulse travel slower than the low frequency components in the normal dispersion regime and the vice-versa happens in the anomalous regime. The anomalous regime plays a vital role in nonlinear fiber optics particularly for the formation of highly stable and distortion less solitons.

Self Phase Modulation (SPM)

Non-linear effect of light-matter interaction is called Self-phase modulation (SPM). Through in self-phase modulation the optical pulse can exhibit a phase shift which prompts the intensity dependent refractive index. A varying refractive index can be prompted in the medium due to the optical Kerr effect through an ultra-short pulse light travelling in a medium which ultimately can produce a phase shift in the pulse causing a change of the pulse's frequency spectrum. This also depends on the intensity of the light because the induced electron cloud polarization in a material does not happen due to a linear function of the light intensity. The degree of polarization increases non-linearly with light intensity. Accordingly, the material causes slowing forces on more intense light. Consequently the refractive index of a material increases with the increase of light intensity.

The intensity dependence of refractive index in fiber optics is known as fiber nonlinearities.

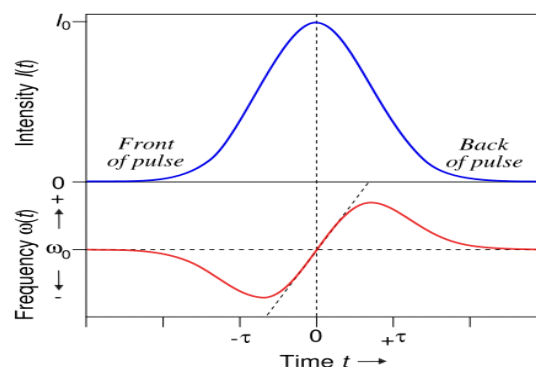


Figure 3: Self Phase Modulation

Figure 3 shows the function of Self phase modulation moving a pulse (top curve) moves through a self-frequency shift (bottom curve) through a non-linear medium. Further, the front of the pulse is also shifted to lower frequencies and again to higher frequencies.

Signal intensity with time leads can to variations in refractive index with time, which is analogous to intensity dependent refractive index. From time to time the phase of signal changes irregularly and cause frequent chirp. These variations in frequencies cause broadening of pulse. Accordingly with high transmission power the variation in such

frequencies are extensively high because the transmission power is directly dependent on frequency chirp. Phase shift by field over fiber length can be calculated by:

$$\phi = 2\pi nL/\lambda \quad (6)$$

Where n = Refractive Index of the Medium, L = Length of the Fiber, λ = Wave-Length of the Optical Pulse, nL = Optical Path Length.

Pulse broadening can be measured in the time domain in SPM. However, the spectral characteristics remain unaltered. The effects of dispersion due to pulse broadening can be reduced by the chirp caused by SPM based on Input power of the signal transmitted. Further in single channel systems, the SPM is a major limitation.

APPLICATIONS OF OPTICAL SOLITON

Soliton Amplification

There occurs loss of energy due to absorption of energy by the fiber as the pulse propagates through a fiber. This effect is called fiber loss. Such a fiber loss causes broadening of solitons which hampers optical communications in particular besides various other applications. This loss is compensated by amplification of the optical pulses. Generally, there are two schemes for soliton amplification known as lumped and distributed amplification schemes. By lumped scheme an optical amplifier boosts the soliton energy to its input level after propagation of soliton through a certain distance. By distributed scheme two methods are applied, i.e., Stimulated Raman scattering and erbium-doped fibers by periodic pumping along the fiber length.

Pulse Compression

Pulse compression means compression of optical pulses which is widely applied on non-linear fiber optics. Dispersive and non-linear effects in optical fibers help in producing pulses less than 5 fs. There are two types of Pulse compressors, one is soliton effect compressors based on nonlinear fiber optics while the other is grating-fiber. Pulse compression happens due to interplay between GVD and SPM. Dispersion-decreasing fibers (DDFs) are helpful for pulse compression. A train of ultra-short pulses can be generated by DDF pulse compression mechanism.

Soliton Bit Rate

With the appropriate use of solitons, most of the commercial terrestrial wave-length division multiplier (WDM) systems, replace the traditional non-return to zero (NRZ) and return to zero (RZ) modulations. NRZ is a binary modulation with square pulses wherein the signal is off for a 0 bit and on for a 1 bit. In RZ one pulse is shorter than the bit time. In NRZ and RZ systems the Kerr nonlinearities (SPM), Cross Phase Modulation (XPM) and Four-Wave Mixing (FWM)) are the unwarranted effects restricting the performance and distorting signals at high speeds. A conventional WDM system enhances the power as much as possible without introducing too much nonlinearity. The NRZ and RZ systems are, therefore, usually known as linear systems. In NRZ system while encoding digital signals if two 1s are close together, the signal intensity does not drop back to 0 between the individual bits as it does with solitons. The conventional NRZ or RZ modulation formats were generally preferred to the soliton based technology. However, the invention of dispersion-managed solitons and commercial application of advanced technologies have played a vital role in increasing the network distances and better bit rates. High local and low average dispersion in the system can be attained through NRZ experiments with dispersion management. The high local dispersion distorts signals and produce intersymbol

interference, i.e. four-wave mixing. Further, it also disrupts the phase matching of different optical frequencies making up a signal. Low average dispersion affects adversely over long spans of optical fiber. The utility of solitons is, therefore, widely acclaimed for advanced terrestrial transport systems.

Timing Jitter

In an ideal soliton in a fiber, the soliton pulses can be separated from each other. Each soliton pulse carries one digit of information bit and it is separate from others. However, it can be possible only when the soliton pulse width becomes much shorter than the bit rates in a larger bandwidth in comparison to a linear pulse having the same bit rate. Soliton timing jitter as a result of amplified noise or due to interactions with neighboring solitons is however, the major detrimental factor to the use of optical soliton communication which is responsible for bit rate error. By dispersion compensation we can control the soliton jitter by reducing the average dispersion close to zero.

Spatial Soliton

With the advent of self-trapping of light the importance of Optical spatial solitons is widely acclaimed. A laser beam focused on the edge of a photo-sensitive material causes its own waveguide which is further guided by this waveguide. Consequently, the diffracted beam of light alters the refractive index of the medium. The beam dynamically creates a channel, with the passage of time, which controls the diffraction and guides the beam through the material. Solitons can be formed with the propagation of an optical beam in a non-linear medium without any diffraction effect. Spatial solitons of various dimensions have been observed in various non-linear media.

CONCLUSIONS

Optical solitons have played a very important and useful role in communication, optical computing, optical switching, etc. The applications of optical solitons are increasing manifolds with the latest technological advancements. We do hope that further extensive and intensive research in this field can yield amazing and marvelous fruits to the future generations.

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